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13. ABSTRACT *(Maximum 200 words)*
A traverse of the Arctic Ocean during a 2000-km unsupported ski expedition provided an opportunity to assess the impact of an extreme cold environment on the protective capabilities of a specialized footwear system (FS). A thermal foot model (TFM) measured thermal resistance (R, m2KW-1) of an FS in new and used conditions. FS consisted of a two-layer sock, a vapor barrier sock, a removable woolen innerboot, a NNN-configured leather/synthetic ski boot, and a waterproof gaiter. When comparing initial total R when dry, the used FS showed an actual increase of 10%. Exposure of the used FS to moisture caused significant reductions in R. Immersing the entire welt of the boot in 8 cm of water for 18 hrs reduced the initial R by a full 34%. Although the used FS had extensive physical wear to the outsole, insole, upper and gaiter, it did not show a reduction in R as a result of the expedition when compared to a new FS. This FS appears to be well chosen as it provided adequate thermal protection to the feet despite exposure to one of the world's most inhospitable climates.

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# EFFECTS OF AN ARCTIC OCEAN SKI TRAVERSE ON THE PROTECTIVE CAPABILITIES OF EXPEDITION FOOTWEAR

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## Introduction

From 16 February to 3 June 2000, two 28-year-old Norwegian Navy SEALs traversed the Arctic Ocean via the geographic North Pole from Cape Arctichesky, Siberia to Ward Hunt Island, Canada during a 1,940-km ski expedition. The expedition was completely self-supported with no resupply from outside sources during the entire trek. Each member began the expedition carrying a 20-kg backpack while pulling two 80- to 100-kg sleds in tandem. After 18 days each member dropped one of the sleds and at 88 days the remaining sleds were dropped leaving each carrying a 40- to 45-kg backpack. Both members wore the same clothing system consisting of a multilayered, extreme cold weather ensemble along with multicomponent headgear, handwear and footwear.

There is limited information on the effects of continuous wear on cold weather personal protective equipment. This expedition provided a unique opportunity to assess the impact of an extreme cold environment on the insulating capabilities of the specialized footwear system (FS) actually worn by one of the expedition members.

## Methods

A thermal foot model (TFM, Figure 1) was used to measure the thermal resistance of the footwear worn by one of the participants in both new, pre-expedition and used, post-expedition conditions (Figure 2). The left-side boot from both the new and used FS was tested in this study due to the left-footed TFM.

The TFM is a copper, life-sized model of the human foot that measures both total and regional thermal resistance, R ($m^2 \cdot K \cdot W^{-1}$). Power input and the calculation of insulation values for the total TFM and its 29 individual sections are controlled by an automated computer system. In this study, the copper surface of the TFM was controlled at 30°C while the climatic chamber housing the TFM was controlled at 20°C and 50% RH. Sectional thermal resistance to heat exchange was calculated using

$$\mathbf{R = A \cdot T / P}$$

where

**A** = area of each individual regional segment, $m^2$,
**T** = temperature gradient between the TFM surface and ambient air temperature, °C, and
**P** = regional power input, W.

Ideally, three separate samples of the same test item(s) are evaluated to minimize differences due to manufacture processes. R values can be converted to the more familiar clo unit (1 clo = 0.155 $m^2 \cdot K \cdot W^{-1}$). TFM data is routinely used to compare standard and prototype footwear, identifying advances in materials, design and manufacturing as part of a final selection process for military procurement purposes. Similar examples of the TFM used in this study are employed worldwide in the evaluation of protective footwear in military, academic, and industrial laboratories.

Additional TFM testing was conducted on only the used FS to simulate the effects of environmental exposure and foot sweating typically experienced during the expedition. This included externally immersing the used FS in shallow water, internally wetting the FS, and periodically spraying the FS with water. Personal communication with the wearer of the FS tested in this study assisted in designing the simulated wetting tests.

The FS consisted of a two-layer sock, a vapor barrier sock, a removable woolen inner boot, a 75 mm norm leather/synthetic ski boot, and a waterproof gaiter. All R values reported are the average result of three separate TFM tests.

**Figure 1.** Diagram showing regional sections of the TFM (left) and photographs showing the TFM bare (center) and during typical military footwear testing (right).

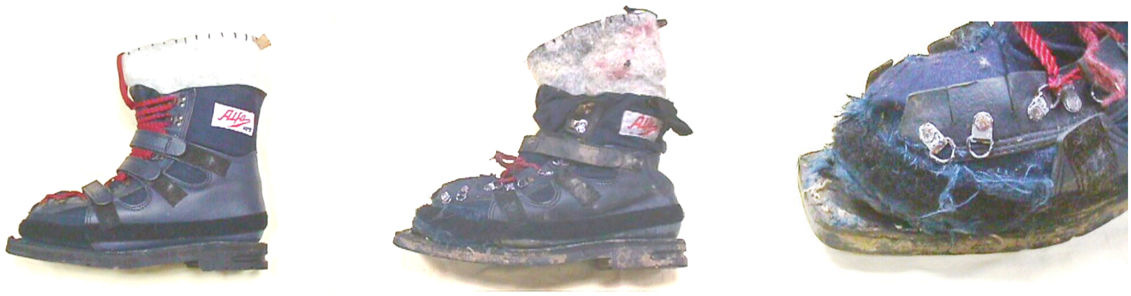

**Figure 2.** Photographs showing the FS in a new, unused condition (left) and after the 109 day Arctic Ocean ski trek (center and right).

## Results

Table 1 shows TFM R values and weights of a new, pre-expedition FS and a used, post-expedition FS when dry and during wear conditions typically encountered during the ski trek. When comparing initial total R of both FS with all components dry, the used FS showed an increase of 10%. Modifications were made to the outer ski boot by the wearer during the course of the trek, including cutting the leather along the D-ring lacing closure and elimination of most of the boot lacing and two of the supportive leather Velcro™ ankle straps. These changes, combined with the undamaged woolen insulation boot, provided the wearer with more boot volume and presumably more foot comfort during use. Dry R values at the toe sections and sole were not different between both FS when dry.

**Table 1**. TFM resistance values (R, $m^2 \cdot K \cdot W^{-1}$) and total weights (kg) of a new, pre-expedition FS and a used, post-expedition FS when dry and during simulated wear conditions. Only the left-side boot of the FS was tested. All R values reported are the average result of three separate TFM tests.

| | **New FS-dry** | **Used FS-dry** | **Used FS-externally wetted**[a] | **Used FS-internally wetted**[b] |
|---|---|---|---|---|
| R, total TFM | 0.248 | 0.276 | 0.183 | 0.143 |
| R, toe sections[c] | 0.310 | 0.318 | 0.104 | 0.095 |
| R, sole section | 0.391 | 0.390 | 0.115 | 0.132 |
| FS weight | 1.64 | 1.62 | 2.40 | 2.56 |

[a] External wetting consisted of immersing the entire welt of the boot in 8 cm of water for 18 hr.
[b] Internal wetting consisted of soaking the two-sock layer in water for 1 hr followed by hand-wringing of excess liquid.
[c] Average R value of the 3 TFM toe sections.

Exposure of the used FS to both external and internal moisture caused large reductions in both total and regional R. External immersion of the entire welt of the boot in 8 cm of water for 18 hrs reduced the

initial R by 34%. Simulated internal sweat-wetting of the two socks caused a 41% reduction from initial R with similar losses at the toes and sole regions of the TFM.

Periodic external spraying of the outer gaiter combined with wet socks resulted in a 46% reduction from initial R. After being allowed to dry for 96 hrs, the used FS regained only 72% of initial total dry R, indicating a large amount of moisture remained within the various insulating layers.

## Discussion

The slight increase in total R of the used FS compared to the new FS was an unexpected result. The physical appearance of the used FS would suggest the opposite result with extensive wear damage to the upper, front outsole and front welt of the test boot. This increase in R is probably the result of the absence of any permanent damage and compression of the custom-made woolen felt inner boot, which represented the greatest insulating component of the FS.

Moisture accumulation within protective footwear from the environment and foot perspiration is unavoidable even during a short duration of wear. A previous TFM evaluation (1) showed similar insulation losses as seen in this study in U.S. military boots utilizing Gore-Tex™ and Thinsulate™ when evaluated during simulated, sustained cold-wet conditions.

The above R losses and the corresponding increases in boot weight when subjected to wetting indicate that the FS probably retained a substantial amount of moisture during the entire expedition. Both expedition members did sustain a moderate case of trench foot while continuously wearing the vapor barrier socks during the early part of the expedition (2).

The U.S. Army invests in a substantial research and development effort to procure protective footwear that provides optimum levels of comfort and protection. As footwear design, materials, and manufacturing processes improve, the TFM test method described here will be instrumental in identifying those that are most effective. A recent inter-laboratory test of the same footwear on 8 different TFM found R value differences mainly related to test climatic conditions, TFM design, and operating procedure (3). Further standardization of TFM design and test procedures would allow for a more universal approach to the development of improved protective footwear.

The U.S. military is concerned about the impact of extremity cooling on soldier performance in cold-wet and cold-dry environments. A physiological cold strain index has been modified to assess peripheral cold stress using measured core and toe temperature (4). Results were found to be consistent with subject behavior and measured toe temperature. Future TFM data combined with physiological responses to cold exposure is expected to enhance these predictive efforts.

## Conclusions

Although the used FS had extensive physical wear to the outsole, insole, upper and gaiter as well as numerous wearer modifications, it did not show a reduction in total R when dry as a result of the expedition when compared to a similar, new FS. In fact, long-term use and modifications of this FS resulted in a small increase in total R while toe and sole values were unchanged. Despite the wear damage, the structural integrity of the outer boot and the insulating inner boot was not affected. Wetting of the various footwear layers of the used FS caused marked reductions in both total and regional R, while retaining moisture that could cause cold injury to the feet during prolonged use.

This specialized footwear system appeared to be well chosen by the expedition members as it provided sufficient thermal insulation during continuous, severe use in one of the world's most inhospitable climates.

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